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THE PROSPECTS FOR SUPERPLASTICITY AT HIGH STRAIN RATES: PRELIMINARY CONSIDERATIONS AND AN EXAMPLE

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1. Introduction

Superplasticity refers to the ability of some fine grained crystalline materials to exhibit extremely large failure strains. Three major requirements for superplasticity have been recognized for over two decades: (i) a fine and reasonably stable grain size, typically <10 μm, (ii) an elevated testing temperature, typically >0.4 T_m, and (iii) a low stress exponent n, typically <2: here $\dot{\epsilon} \propto \sigma^n$, $\dot{\epsilon}$ is the strain rate and σ is the stress.

The requirement for a fine and stable grain size has generally restricted the observation of superplasticity to either microduplex alloys, where chemical differences across boundaries restrict grain growth, or quasi-single phase alloys, where fine precipitates pin the grain boundaries to limit grain growth. However, superplasticity may be observed in fine grained pure metals and solid solution alloys, as long as the exposure to high temperature is short enough to preclude excessive grain growth. In the context of the present paper, Baudelet [1] utilized this idea to demonstrate superplasticity in a single phase Cu-P alloy. Also, superplasticity has been reported in single phase alumina by Venkatachari and Raj [2], where the fine grain size is reasonably stable at the testing temperature.

It is proposed that high strain rate deformation in conventionally coarse grained metals can lead to dynamic recrystallization with an attendant grain size reduction that is conducive to superplasticity. At high strain rates of $>10^3$ s^{-1}, the deformation process is essentially adiabatic; plastic deformation at room temperature can lead to high temperatures of $T_h \gtrsim 0.4$ (where T_h is the homologous temperature) that are required for dynamic recrystallization. Both Sandstrom and Lagneborg (3) and Derby and Ashby (4) developed analytical expressions of the form $d_s \propto \dot{\epsilon}^{-0.5}$, where d_s is the steady state recrystallized grain size. Section 2 provides a more detailed account of these concepts.

An important experimental observation relating to the optimum strain rate for superplasticity, $\dot{\epsilon}_{opt}$, is that it is increased to higher values with a decrease in grain size. This is demonstrated in Fig. 1, which shows experimental results from a superplastic Al-33% Cu eutectic alloy (5) and a mechanically alloyed Al90211 alloy (6) in the form of a plot of the elongation to failure vs strain rate. These two alloys had grain sizes of ~7 and 0.5 μm, respectively. Fig. 1 reveals that the optimum strain rates for superplasticity in these alloys are $\sim 10^{-4}$ and 10 s^{-1}. In general, the optimum strain rate is related to the grain size, d, as follows:

$$\dot{\epsilon}_{opt} \propto d^{-q} \tag{1}$$

where the exponent q has a value between 2 and 3 (7).

Extrapolation of the experimental data shown in Fig. 1 suggests that superplasticity may be attained at strain rates of $>10^4$ s^{-1} in materials with grain sizes of <0.05 μm.

Thus, the increase in strain rate produces two effects that promote superplasticity: (i) an adiabatic temperature rise and (ii) a reduction in the recrystallized grain size.

These concepts are applied to a specific example - the shaped charge - in Section 3, where it is demonstrated that the extraordinarily high strains undergone by the shaped charge jets can be explained by high strain rate superplasticity.

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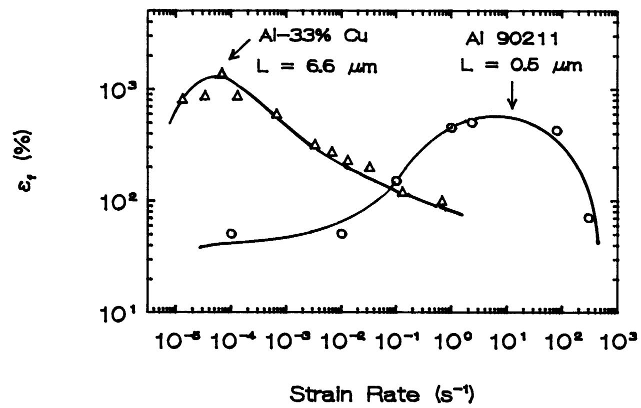


Fig. 1 The variation in elongation to failure, ϵ_f, with strain rate for the Al-33% Cu (5) and the mechanically alloyed Al90211 (6) superplastic alloys.

2. Analysis

2.1 Adiabatic Temperature Rise

The temperature rise accompanying plastic deformation can be estimated from the plastic deformation energy. It is known that ~90% of deformation energy is converted to heat. Assuming a constant heat capacity, c_p, the temperature rise, ΔT, is

$$\Delta T = \frac{0.9}{\rho c_p} \int_0^{\epsilon} \sigma \, d\epsilon \tag{2}$$

where ϵ is the plastic strain and ρ is the density of the material.

The following simple constitutive model for the stress as a function of homologous temperature, T_h ($=T/T_m$, where T is absolute temperature and T_m is the absolute melting temperature), strain and strain rate was proposed by Johnson and Cook (8):

$$\sigma = (\sigma_0 + B\epsilon^N)\ (1 + C\ell n\dot{\epsilon}^*)\ (1 - T_h^M) \tag{3}$$

where σ_0 is the yield stress, B, C, N, and M are constants and $\dot{\epsilon}^*$ ($=\dot{\epsilon}/\dot{\epsilon}_0$) is the normalized strain rate ($\dot{\epsilon}$ is the imposed strain rate and $\dot{\epsilon}_0 = 1\ s^{-1}$). Equations 2 and 3 may be combined as follows by assuming a constant strain rate:

$$\int_{T_0^*}^{T_f^*} \frac{dT}{1 - T_h^M} = \frac{0.9\ (1 + C \ln \dot{\epsilon}^*)}{c_p \rho} \int_0^{\epsilon_f} \left(\sigma_0 + B\epsilon^N\right) d\epsilon \tag{4}$$

where T_0^* and T_f^* are the initial and final homologous temperatures, respectively. The solution to Eqn 4 gives the temperature rise as a function of plastic deformation.

2.2 Dynamic Recrystallization

Dynamic recrystallization plays an important role in many plastic deformation processes. The experimental results and theoretical aspects of this phenomenon have been reviewed by McQueen and Baudelet (9), Sakai and Jonas (10) and Ueki et al. (11). Dynamic recrystallization essentially involves the development of a dislocation cell and sub-grain structure and the transformation of low angle grain boundaries to high angle grain boundaries during plastic deformation. The process is repeated continuously during deformation, and leads eventually to the development of a steady-state recrystallized grain size, d_s. Dynamic recrystallization is a thermally activated process, which is important at temperatures greater than 0.4 T_m.

From the theory for dynamic recrystallization developed by Sandstrom and Lagneborg (3), it is possible to obtain the recrystallized steady-state grain size as a function of the number of recrystallization nuclei per grain, N_r, the grain boundary energy (γ) and mobility (m^*), the imposed strain rate and the critical strain for recrystallization, ϵ_{cr}. Using the equations provided by Sandstrom and Lagneborg (3), d_s may be expressed effectively as:

$$d_s \simeq (3\epsilon_{cr} m^* \gamma / \dot{\epsilon}\, \ell n\ N_r)^{1/2} \tag{5}$$

Derby and Ashby (4) obtained the following expression for d_s:

$$d_s = (2^{n_c - 1} \epsilon_c \lambda g / 3\dot{\epsilon})^{1/2} \tag{6}$$

where n_c is the critical number of cell intersections with grain boundaries, ϵ_c is the characteristic strain to reach steady-state, λ is the steady-state sub-grain size and g is the grain boundary growth rate.

It is important to note that, in spite of the different approaches used by Sandstrom and Lagneborg (3) and Derby and Ashby (4), both models predict the proportionality

$$d_s \propto \dot{\epsilon}^{-0.5} \tag{7}$$

2.3 Effect of Strain Rate on Requirements for Superplasticity

The feasibility of superplasticity at high strain rates may be examined by using a constitutive model for superplastic deformation for a comparison of theoretical predictions with experimental conditions. The rate controlling mechanism for superplastic deformation has not yet been identified unambiguously (12). However, it is generally accepted that the Coble diffusion creep mechanism may be used as a lower limit of strain rate for superplasticity. The Coble diffusion creep mechanism predicts the following expression for the creep rate, $\dot{\epsilon}_{Co}$ (13):

$$\dot{\epsilon}_{Co} = \frac{150\Omega\delta D_{gb}\sigma}{\pi k T d^3} \tag{8}$$

where Ω is the atomic volume, δ is the width of the grain boundary, D_{gb} is the grain boundary diffusion coefficient and k is Boltzmann's constant. Since the Coble creep mechanism gives a lower limiting strain rate, superplasticity is likely to occur at strain rates higher than those given by Eqn 8.

3. An Example of High-Strain, High-Strain-Rate Deformation: The Shaped Charge

The shaped charge, analyzed in detail by Birkhoff _et al_. (14), is one of the high strain rate applications involving high strains. In this section, the principal mode of deformation undergone by a metal will be described qualitatively and the aforementioned concepts in Section 2 will be applied quantitatively: it will be demonstrated that micrograin superplasticity by Coble creep can contribute to the extremely high tensile strains (>20) exhibited by the metal under the imposed experimental conditions. However, other novel mechanisms linked to dynamic recrystallization, and heretofore not identified, deserve to be explored.

Figure 2 shows schematically the principle of operation of a shaped charge. A cylindrical explosive charge with a conical shaped cavity lined with a metal is detonated along the axis of symmetry at the end closest to the cone apex. The shock wave and high gas pressures produce the collapse of the cone. Birkhoff _et al_. (14) treated the liner as a fluid and defined a stagnation point at the convergent apex (A). The material is deformed under compression (convergence to the apex), and subsequently the portion on the right hand side of the apex is stretched in tension along the cone axis, thereby imposing large strains on the jet. Significant strains can be achieved during the compressive deformation. This tensile deformation, following the compressive collapse of the cone, is the result of a velocity differential within the jet and the slug (Fig. 2c), $v_1 > v_0$. It was originally thought that the high ductility exhibited by the jet was the result of it being molten, but more recent experiments by flash x-ray diffraction demonstrate conclusively that for Al and Cu the jet is actually solid (15,16). The practical commercial application of shaped charges includes, for example, the recovery of oil from underground reserves.

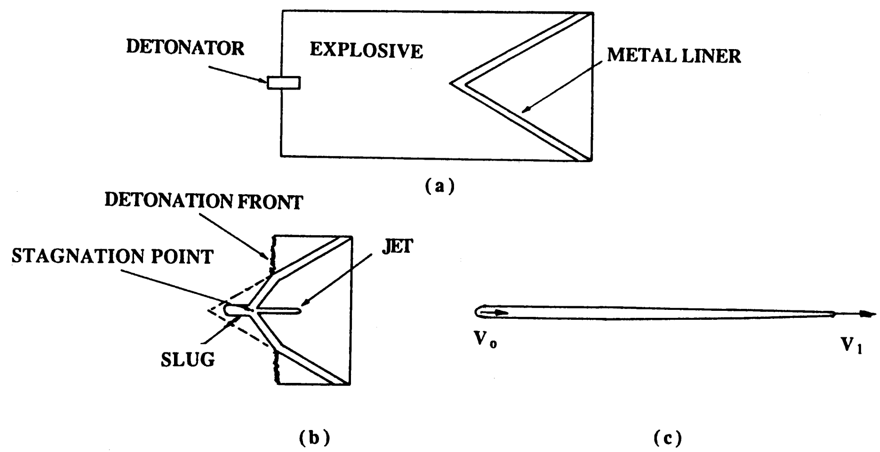


Fig. 2 Schematic illustration of the deformation of a shaped charge liner: (a) initial configuration, (b) after partial compressive collapse and (c) after tensile elongation.

It is proposed herein that the compressive deformation produced by the collapse of the liner leads to a temperature increase and strains sufficient to dynamically recrystallize the microstructure. The calculations supporting this suggestion are shown below for copper, a common liner material.

3.1 The Adiabatic Temperature Rise

Calculations for a typical Cu shaped charge reveal that the strain rates achieved are of the order of $>10^4\ s^{-1}$. Johnson and Cook (8) reported a value of M=1.09 for Cu; for the purposes of the present approximate calculations, it is assumed that M=1 in Eqn 4. The temperature rise occurring during the dynamic deformation of Cu at room temperature and at a strain rate of $10^4\ s^{-1}$ was estimated using values of the other parameters reported by Johnson and Cook (8). The results of these calculations are shown in Fig. 3 as a plot of temperature versus strain.

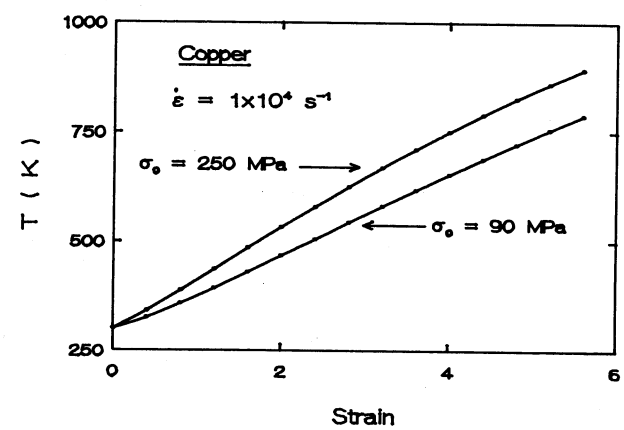


Fig. 3 The variation in the temperature with plastic strain during the dynamic adiabatic deformation of copper at a strain rate of $10^4\ s^{-1}$; initial temperature = 298 K.

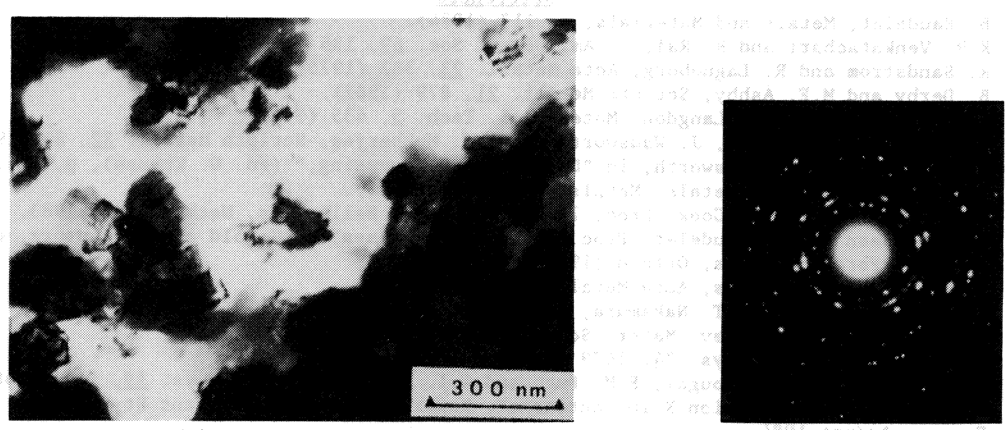
The calculations were performed for two different values of the yield stress for copper, σ_0 = 90 and 250 MPa. A yield stress σ_0=90 MPa was reported by Johnson and Cook (8); the higher yield stress of 250 MPa accounts for the influence of shock hardening on yield stress. The explosive in direct contact with the liner shock hardens it prior to the actual compressive collapse. The passage of a shock wave of an amplitude estimated to be ~50 GPa (17) increases the flow stress σ_0 from 90 to $\gtrsim$250 MPa (18).

Inspection of Fig. 3 reveals that temperatures of >0.4 T_m may be achieved by plastic strains of $\gtrsim$3. It is also noted that an increase in the yield stress, by shock hardening, decreases the strains necessary to achieve a given temperature. Dynamic recrystallization generally occurs at temperatures of >0.4 T_m. Approximate calculations show that shaped charges experience strains of$\gtrsim$5 during the initial collapse. Consequently, the compressive deformation of shaped charges satisfies the experimental conditions necessary for dynamic recrystallization.

3.2 Dynamic Recrystallization and Superplasticity

The grain sizes obtained by dynamic recrystallization at a strain rate of 10^4 s^{-1} can be established from Eqns 5 and 6. However, the material and deformation parameters in these equations are poorly established; consequently, a more realistic approach is to determine the constant of proportionality between d_s and $\dot{\epsilon}$, Eqn 7, by means of the data existing in the literature.

Ueki et al. (11) conducted measurements of the dynamically recrystallized grain size of copper over a range of experimental conditions. Their experimental data reveal that the steady-state grain size is ~15 μm at a strain rate of ~6×10^{-1} s^{-1} (11). Using these results in conjunction with Eqn 7, it is anticipated that sub-micron grain sizes of $\lesssim$0.1 μm may be attained at strain rates of $\gtrsim10^4$ s^{-1}. Equation 8 is then used to calculate the strain rate due to the Coble creep mechanism. The grain boundary diffusion coefficient may be expressed as $D_{gb} = D_{0gb} \exp(-Q_{gb}/RT)$, where D_{0gb} is a frequency factor, Q_{gb} is the activation energy for grain boundary diffusion and R is the gas constant (=8.31JK^{-1}). Equation 8 was evaluated for copper using the following values for the parameters: $\delta D_{gb} = 5\times10^{-15} \exp(-104000/RT)$ m^3s^{-1}, $\Omega = 1.2\times10^{-29}$ m^3, σ = 300 MPa and T = 750 K. The calculations reveal that strain rates of $\gtrsim10^4$ s^{-1} may be attained for materials with grain sizes of $\lesssim$0.01 μm. Since the Coble creep mechanism gives a lower limiting strain rate, it is anticipated that superplasticity can be attained at either higher strain rates, for the above grain size, or a lower grain size, for the above strain rate. Thus, the grain size reduction achieved by the dynamic recrystallization process at >10^4 s^{-1} is compatible with the conditions required for superplastic deformation at high strain rates.



(a) (b)

Fig. 4 The internal microstructure of a deformed copper shaped charge slug: (a) bright field micrograph illustrating the fine recrystallized grain size and (b) rings in the corresponding diffraction pattern confirming the microcrystalline nature of the specimen.

3.3 Experimental Evidence

A deformed shaped charge Cu liner slug was obtained and examined by transmission electron microscopy. Figure 4a is a bright field transmission electron micrograph illustrating the sub-micron grain size of the material. The rings in the diffraction pattern shown in Fig. 4b confirm the microcrystalline nature of the specimen. Although the microstructure observed is likely to have undergone changes (grain growth) during the cooling cycle, after the large superplastic tensile deformation, the observations are still indicative of the very fine microstructure that develops during the dynamic deformation process.

3.4 Closing Comments

Previous analyses of the tensile deformation of shaped charges have related the stability of deformation to the presence of an inertial confining pressure as a consequence of a radial velocity gradient across the axis of a deforming shaped charge (19,20). The present report suggests that the development of a fine grained microstructure, by dynamic recrystallization, may provide an important additional contribution to the stability of tensile deformation. Depending on the experimental conditions imposed, relating to the conditions necessary for dynamic recrystallization, this new mechanism is likely to become important either at the onset of tensile deformation or after some tensile deformation has been achieved under a superimposed confining pressure.

4. Summary and Conclusions

The preliminary considerations outlined in this report indicate that high strain rate deformation leads to a substantial increase in temperature which, when coupled to the large strains involved, leads to a very fine sub-micrometer grain size microstructure by dynamic recrystallization. Subsequently, the fine grain size promotes superplasticity at high strain rates, which leads to large tensile strains to failure. These concepts are developed quantitatively and it is demonstrated that they may provide an important additional contribution to the experimental observation of superplasticity at high strain rates in copper shaped charge liners.

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